

NONDESTRUCTIVE EVALUATION OF GRAPHITE/EPOXY COMPOSITE DAMAGE

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ABSTRACT

Ultrasonic and acoustic emission techniques were used to monitor and evaluate material damage in a graphite/epoxy laminate containing a machined hole as an initial flaw and subjected to fully reversed spectrum fatigue loading at room temperature. It was found that the flaw growth progressed radially around the initial hole at a uniform rate during cycling at the lower stress levels. At the higher levels, material damage accelerated dramatically, progressing faster in the transverse direction toward the free edges. By close examination of the A-scan and RF spectrum photographs, it was determined that damage modes could be defined as to their extent and relative location within the specimen. These conclusions were supported by photographs of the failed specimen.

EXPERIMENTAL PROCEDURE

Specimen - The specimen was a 16-ply graphite/epoxy (AS3501-5A) coupon of $[(0/\pm 45/90)_5]_2$ layup. The specimen gage section was 5.08 cm (2 in.) long and 3.81 cm (1.5 in.) wide. The initial flaw was a 0.795 cm (0.313 in.) diameter hole bored into a previously unflawed/undamaged specimen. The hole was drilled using a diamond tipped coring bit mounted on a variable speed drill press. Figure 1 shows the specimen after the hole was drilled and before fatigue loading was begun. The fiber damage around the hole was caused by the coring bit when it penetrated the back-side of laminate. An ultrasonic C-scan of the specimen, Fig. 2, and corresponding A-scans, showed the damage was superficial. Previous experience indicated that this type of superficial damage does not influence appreciably material damage caused by fatigue loading.

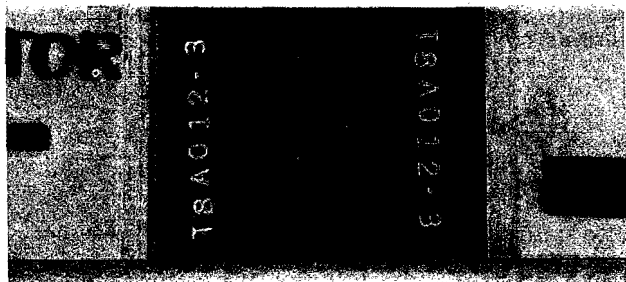


Fig. 1

Test Specimen with Initial Flaw (Hole)
Before Fatigue Loading

Loading - The test specimen was preconditioned by oven-drying at 347 deg K (165°F) for five days. The specimen was tested under ambient environmental conditions because the acoustic emission transducers did not work well in humid and/or hot environments.

The specimen was stress-cycled in a five-position chain, with load applied through an electrohydraulic closed-loop system. The load spectrum consisted of 127,500 cycles of tension-compression at various levels of peak stress per life-time. At a cycling frequency of three Hertz, this was accomplished in approximately twelve hours. The

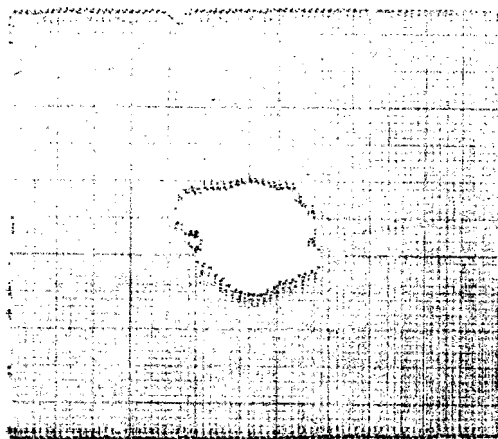


Fig. 2

C-scan of Test Specimen with Initial
Flaw (Hole) Before Fatigue Loading

specimen studied was cycled to peak levels of 161 MPa (23 ksi), 223 MPa (32 ksi) and 276 MPa (40 ksi) applied over 510,000, 510,000, and 254,428 cycles, respectively, in an effort to accelerate and extend the material damage.

NONDESTRUCTIVE MONITORING

Acoustic Emission² - The acoustic emission system consisted of 0.95 cm (0.38 in.) diameter broadband transducers operational in the 0 to 1 MHz range. A transducer was attached to the specimen using a clip and an acoustic coupling medium to minimize the entrance of extraneous transient noise into the system, Fig. 3. The acoustic signal was fed into a databus after being processed by 180 to 210 KHz filters and then by preamplifiers. The databus operated at a 0.1 sec. sampling rate feeding an eight channel event recorder and chart recorder for hard copies of the data. Acoustic emission records consisted of both instantaneous rate and cumulative counts recorded for the entire fatigue spectrum.

As mentioned earlier, filters were used between the acoustic emission transducer and recorders. The frequency band of these filters was carefully selected to allow only noise generated by the

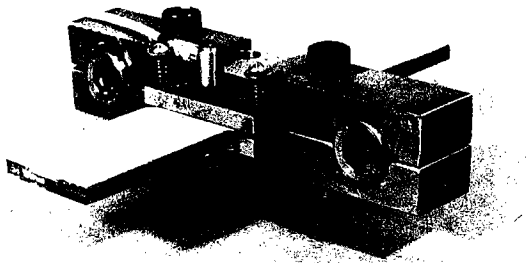


Fig. 3

Specimen with Compression Stabilization Plates
and Acoustic Emission Transducer

specimen to be recorded. The filter frequency band was determined by testing until all extraneous noises could be identified and blocked out. Also, to guarantee that no other sound sources existed, the specimen was the only one present in the fatigue chain during testing. The remaining four positions were filled with aluminum "dummy" specimens. Whenever possible the specimen was run at night when the chance of picking up background noise from other electric equipment was at a minimum.

Ultrasonic Monitoring³ - At intervals corresponding to each half lifetime of loading, the specimens were removed from the fatigue machine and inspected ultrasonically. The ultrasound was transmitted and received with a single 5 MHz focused immersion transducer of 2.54 cm (1.0 in.) diameter and 6.35 cm (2.5 in.) focal length. These dimensions produce a focal spot of approximately 1.27 mm (0.05 in.) in diameter, which is comparable to the thickness of commonly inspected laminates.

The transducer was operated by an ultrasonic analyzer operating in the pulse echo mode. The analyzer provides a time domain output for viewing the received pulse on an oscilloscope (A-scan) and a peak output detector for detecting and recording the local peak within the gated portion of the pulse.

The scanning system that was used to inspect the specimen is capable of automatically scanning and indexing the transducer so specimens up to approximately 38 cm (15 in.) square can be inspected with a single positioning.

The transducer is linked to an X-Y recorder via displacement transducers so that a hard copy of the data can be generated. Figure 4 shows the various types of scans which can be generated by the system at this time. Figure 4a is a C-scan representation of a [(0/±45/90)_s]₂ graphite/epoxy specimen with an initial flaw in the form of a circular hole. In this mode an alarm circuit with two limits is used

which causes the pen to lift from the paper whenever the set limits are exceeded. These limits were determined using a standard specimen.

Figure 4b is an analog scan of the same specimen. In this mode the gated peak voltage of the reflected pulse is recorded as a deflection of the pen normal to the scanning direction. The variations of this voltage are related to the presence of flaws.

Figure 4c is an offset angle analog scan of the same specimen. In this mode a component of the X-axis signal is fed into the Y-axis signal resulting in a perspective view of the specimen. Flaws now appear as troughs and gray tones on a uniformly displaced background.

When a series of C-scans for one specimen are superimposed upon one another a flaw map is generated. In this way the total flaw growth history for a specimen can be presented in one illustration.

The ultrasonic scanning was rigidly controlled with all variable setting controls considered frozen throughout the test. A fixture was used to insure the relative position of the specimen to the scanning transducer for each inspection. Usually the C-scan is the only hard copy representation of a specimen under normal conditions, but this is only a small part of the data available by ultrasonic inspection. In addition to C-scans, such as Fig. 2, the ultrasonic wave was analyzed and recorded on a spot basis by photographing the ultrasonic pulse on the oscilloscope (A-scan) and the frequency spectrum of the pulse.

GENERAL PROCEDURES

To minimize the possibility of generating false or misleading data extreme care was taken during the testing procedure. The testing, including insertion and removal from the fatigue machine, attachment and removal of the acoustic transducer, and ultrasonic scanning, was conducted by one person. Photographs, such as shown in Fig. 1 were taken at regular intervals to supplement the acoustic emission and ultrasonic data. Due to its operation characteristics the ultrasonic scanner may not pick up surface irregularities which can be seen if the specimen is inspected visually.

To avoid damage to the specimen during insertion or removal from the chain a special torquing sequence was developed for the grip bolts. This sequence required the use of a preset torque wrench which would assure satisfactory gripping forces on the tabs of the specimen without causing bending or damage to the specimen. Also, to avoid buckling or bending of the specimen during loading, stabilization plates, visible in Fig. 3, were attached over the center of the specimen gage section. A teflon film was placed on the stabilization plate to minimize friction and extraneous noises.

RESULTS

Acoustic Emission² - Figure 5 shows flaw maps of the cumulative damage through 0, 4, 8, and just before 10 lifetimes, respectively. As was seen for other specimens with this initial flaw type,¹ the flawed area increased in a generally radial pattern around the hole at a nearly uniform rate. The damage indicated in Fig. 5a is associated with the fiber breakage caused when the hole was machined. The rapid

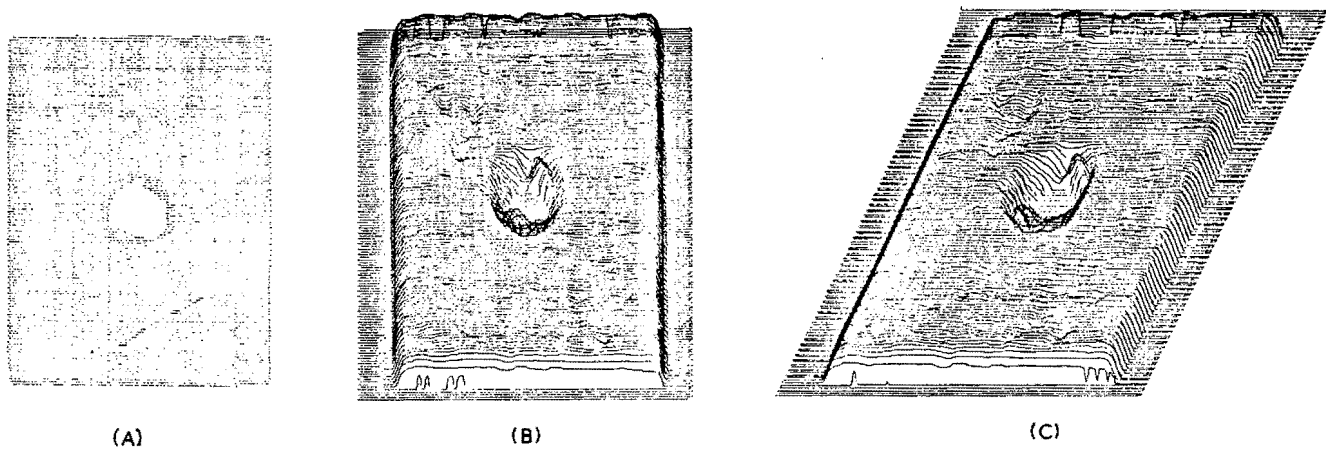


Fig. 4

Ultrasonic C-scans of $[(0/\pm 45/90)_s]_2$ Graphite/Epoxy Specimen with a Circular Hole
(a) Pen-Lift Scan, (b) Analog Scan (Normal), (c) Analog Scan (Perspective)

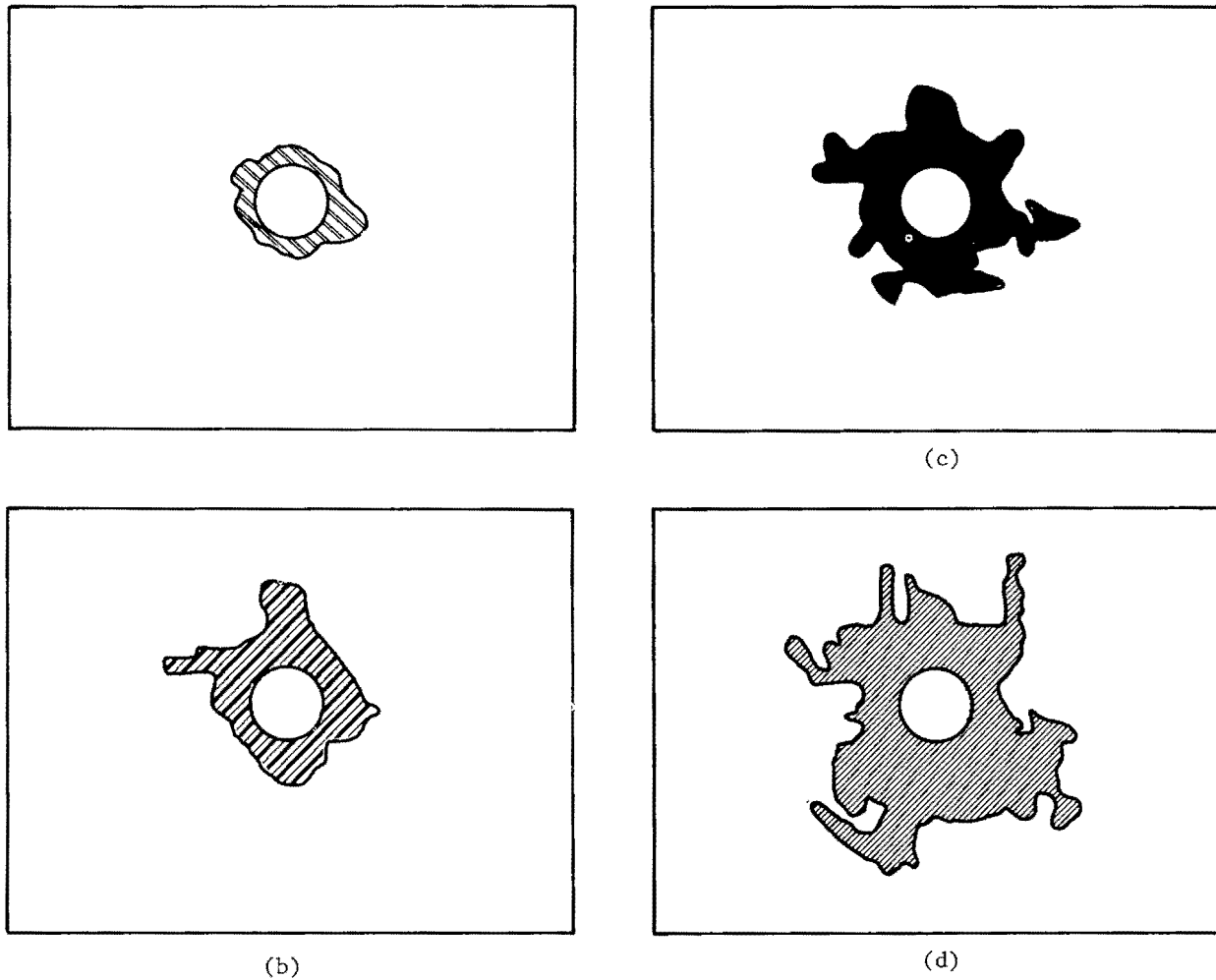


Fig. 5

Cumulative Flaw Growth Under Fatigue Loading in $[(0/\pm 45/90)_s]_2$ Graphite/Epoxy Specimen with Circular Hole. (a) Initial Flaws, (b) Four Lifetimes, (c) Eight Lifetimes, and (d) Nearly Ten Lifetimes

acceleration of the flaw damage between Figs. 5c and 5d was expected because the maximum testing stress of 223 MPa (32 ksi) specified in the initial program for this material was exceeded. The maximum peak stress of 276 MPa (40 ksi) was applied at the end of eight lifetimes of testing and maintained until failure, which occurred very near the end of the tenth lifetime (1, 274, 428 cycles).

The acoustic emission charts for the first eight lifetimes were definitely in keeping with the relative damage indicated by ultrasonic inspection. Very little acoustic activity was present during this period and it was of a uniform intensity level with the major peaks occurring when high load was applied for short periods. This implies that what little damage did occur during each half-life happened at the higher load levels.

Previous work in monitoring graphite/epoxy laminates under static load indicated that we should not have expected major activity until the 223 MPa (32 ksi) stress limit was surpassed. Figures 6 and 7 show acoustic emission records between 8½ and 10 lifetimes when extensive flow growth was detected ultrasonically.

Figure 6 shows a general increase in the acoustic emission response at peak loads while the response to low load applications decreases during the 9th lifetime. Acoustic emission activity increases generally after 8½ lifetimes up to a point where a large amount of activity is recorded culminating in a massive burst (arrow in Fig. 7). Close examination of the specimen after the 19th half-lifetime showed the presence of a large delamination visible on the boundary of the circular hole. Since no sign of such damage was present before the 19th half-lifetime it has been concluded that the formation of the delamination coincided with the acoustic emission burst. Since the specimen failed before completion of the half lifetime following the one where the massive burst occurred, it is safe to say that the acoustic emission indicated, if not predicted, that failure was imminent.

The specimen failed after 1,274,428 cycles were applied (nearly 10 lifetimes), the load at failure was 22.68 kN (5099 lb) corresponding to a stress level of 276 MPa (40 ksi). Figure 8 shows the failed specimen in the load chain. The specimen failed at the center of the gage section through the circular hole; this indicates that the failure

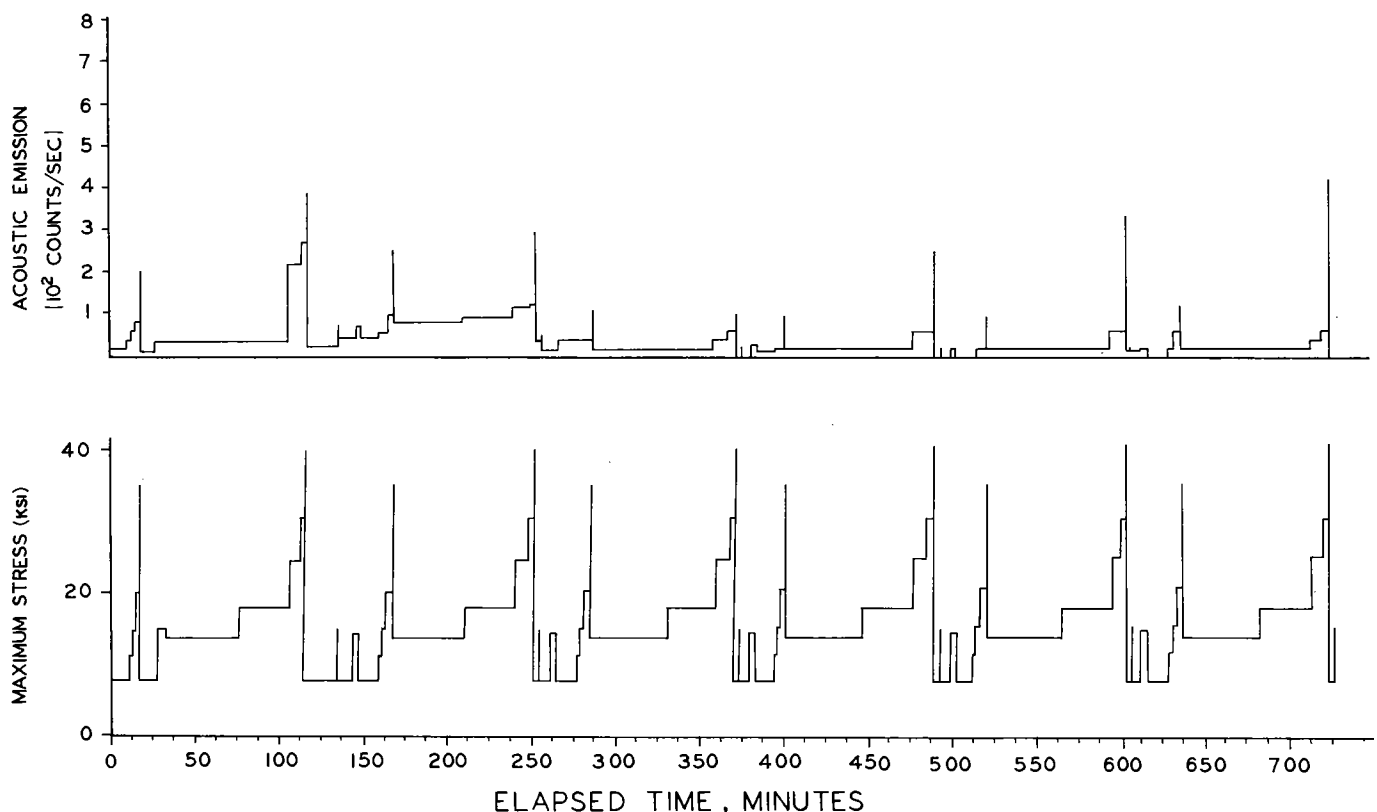


Fig. 6
Acoustic Emission and Corresponding Load Spectrum for $[(0/\pm 45/90)_S]_2$ Graphite/Epoxy Specimen with Hole for 8½ and 9 Lifetimes

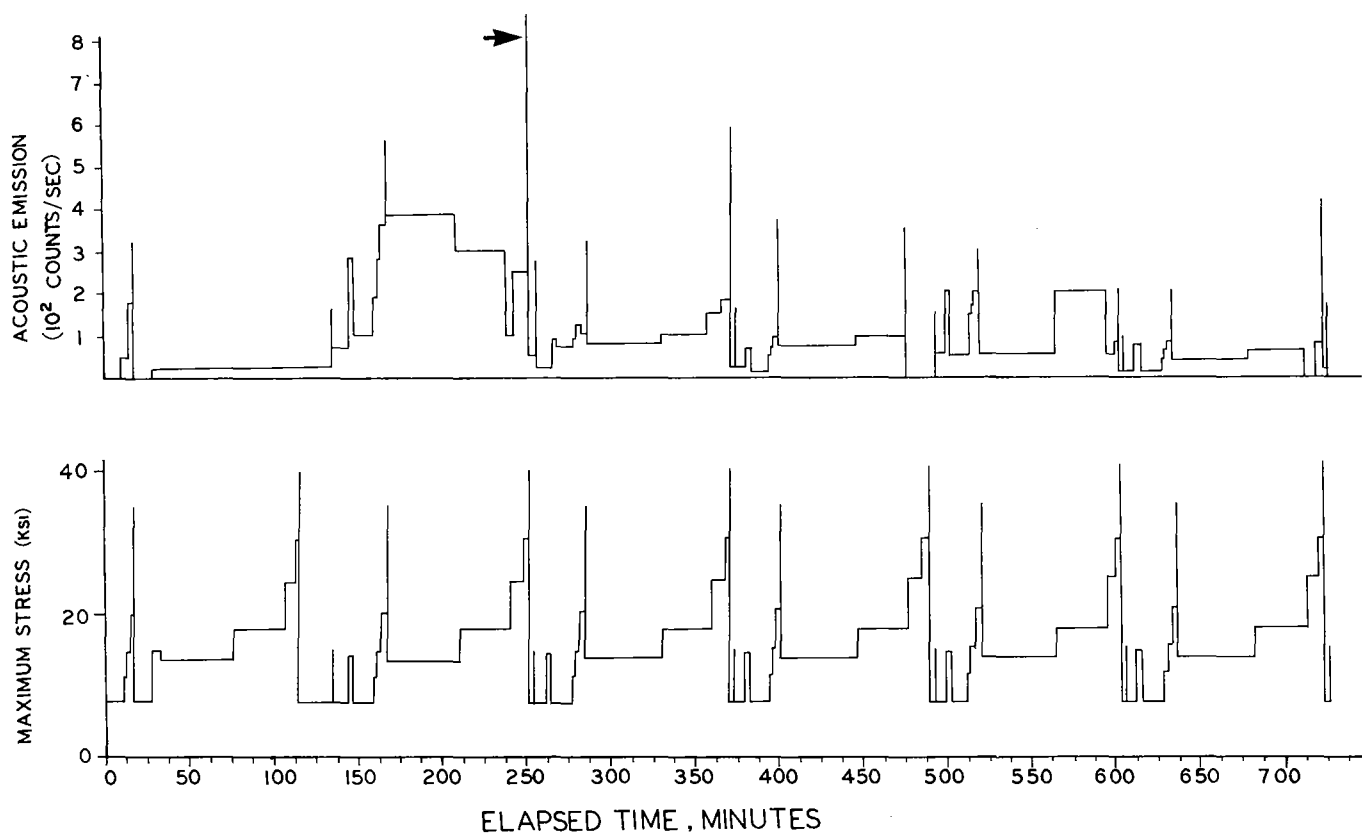


Fig. 7

Acoustic Emission and Corresponding Load Spectrum for $[(0/\pm 45/90)_5]_2$ Graphite/Epoxy Specimen with Hole for $9\frac{1}{2}$ and 10 lifetimes

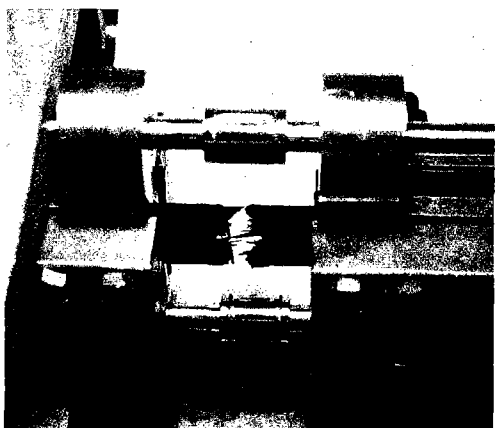


Fig. 8

Failed Specimen in Fatigue Chain

mechanism was material fatigue, not failure, due to bending of the specimen or overtightening of the grips.

Ultrasonic Monitoring - Figures 9, 10, and 11 show representative C-scan, A-scan and RF spectrum data for the test specimen at the indicated inspection times. Figure 9a shows the baseline responses of the A-scan and RF spectrum when no material is seen by the ultrasonic wave. The scatter on the RF spectrum is due to feedback noise from the A-scan oscilloscope. Figure 9b shows the baseline A-scan and RF spectrum responses when the ultrasound passes through an undamaged section of the specimen.

Figure 9c through 11b show how the A-scan and RF spectrum change as fatigue cycles are accumulated. C-scan inspections at 4, 5, and $5\frac{1}{2}$ lifetimes (Figs. 9, 10a, and 10b, respectively) indicate little damage growth in the area of the point of analysis. In contrast, the A-scans and RF spectra have changed appreciably from those in Fig. 9 indicating a definite change in the material integrity near the point of analysis. The characteristic which indicates the material degradation is the back-face reflection of the A-scan wave. The level of ultrasound attenuation, which indicates the presence and severity of an abnormality in the material, is represented by a change in the amplitude of the back-face reflection,

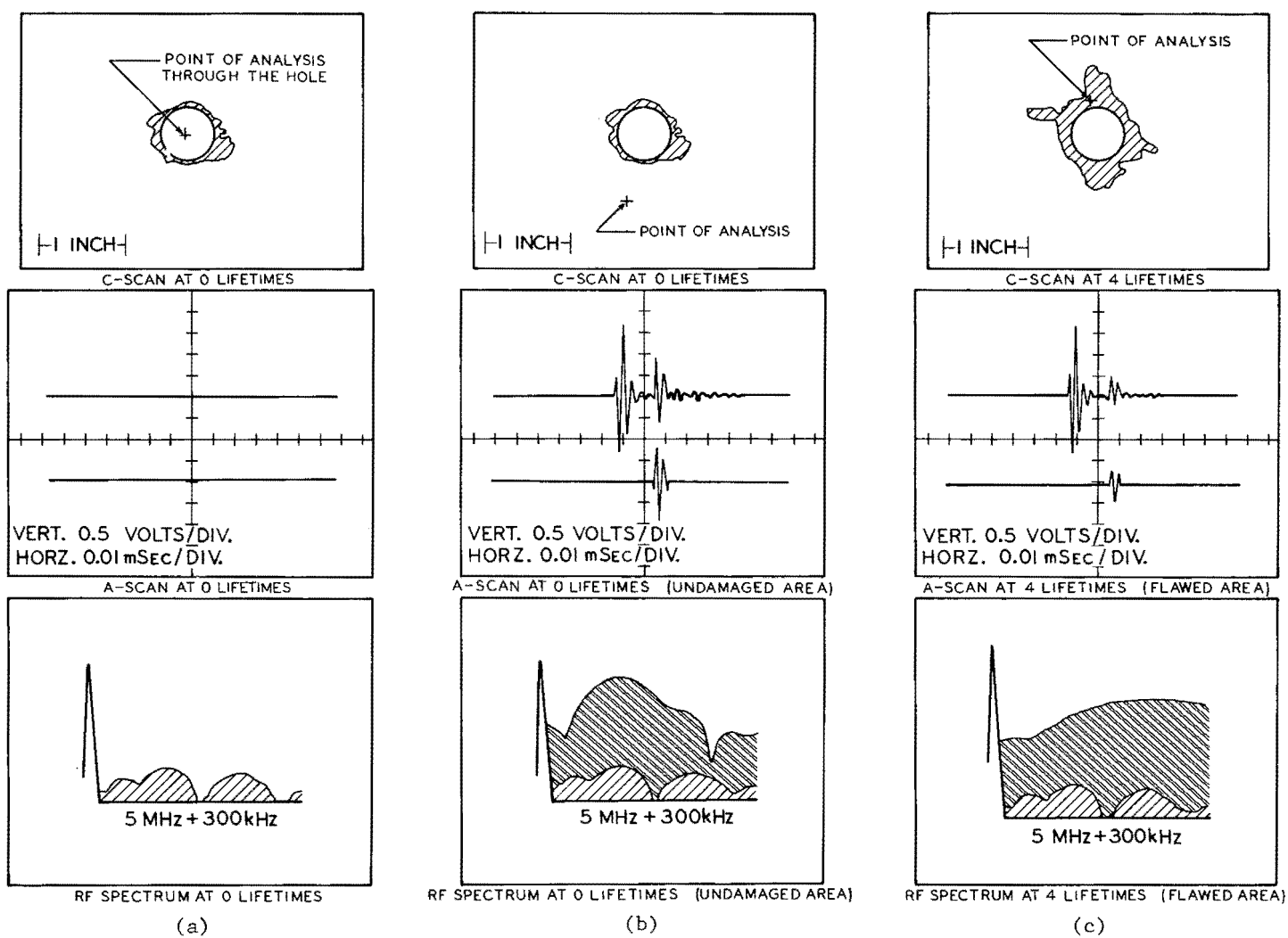


Fig. 9
Ultrasonic Inspection Data at the Indicated Point of Analysis After
(a) 0, (b) 0, and (c) 4 Lifetimes of Load Application

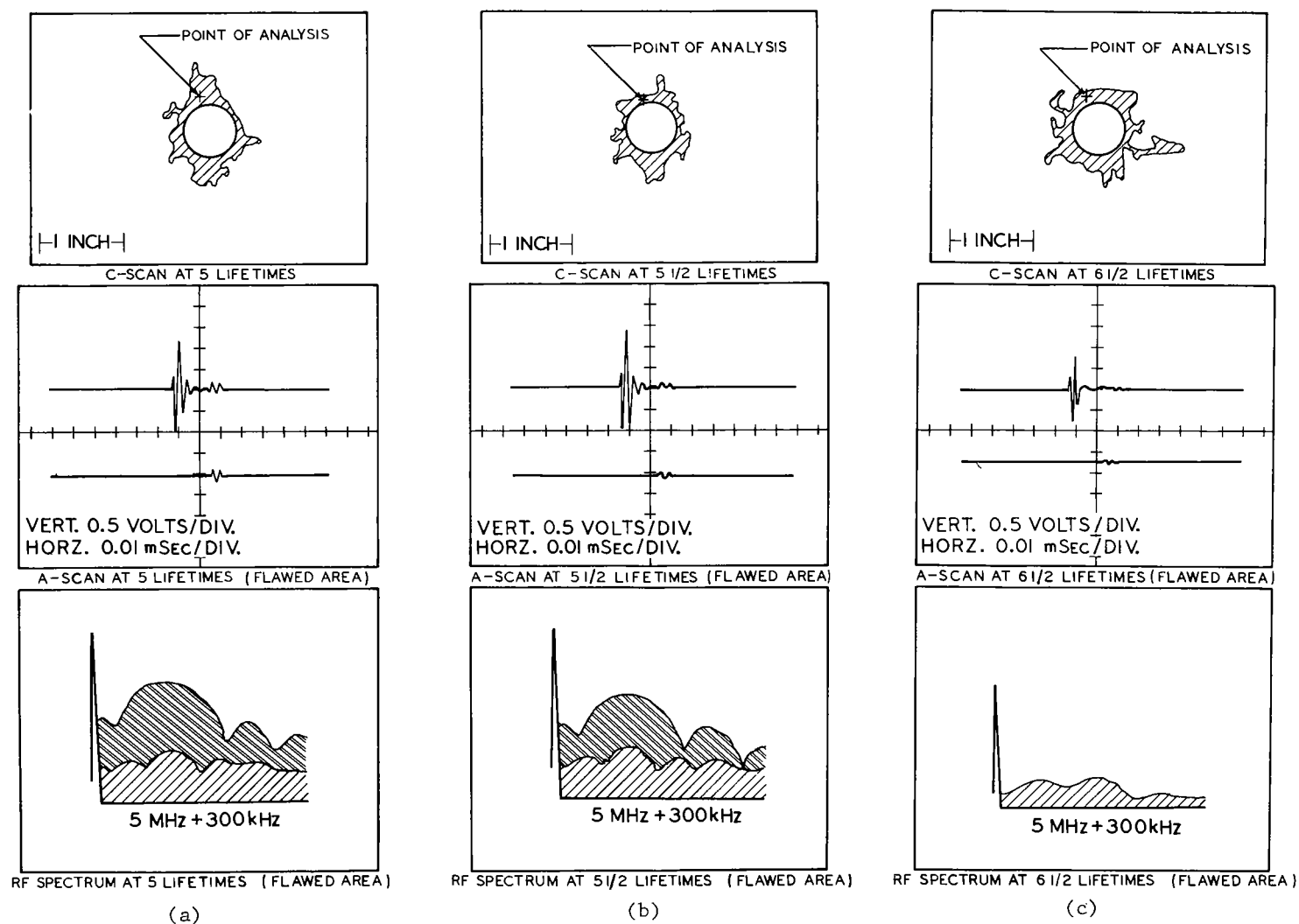


Fig. 10
Ultrasonic Inspection Data at the Indicated Point of Analysis After
(a) 5, (b) 5½, and (c) 6½ Lifetimes of Load Application

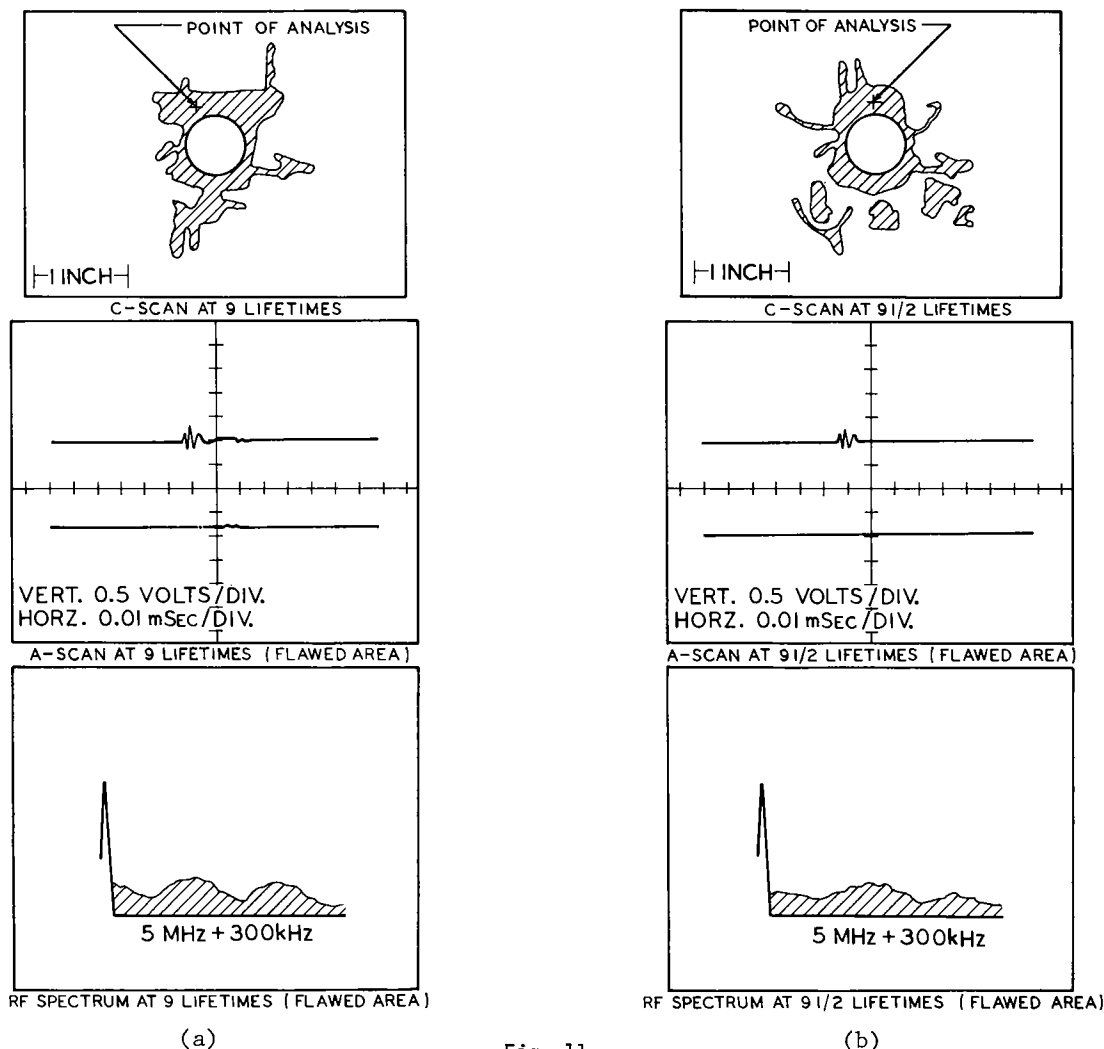


Fig. 11
Ultrasonic Inspection Data at the Indicated Point of Analysis After
(a) 9 and (b) $9\frac{1}{2}$ Lifetimes of Load Application

of the ultrasonic wave. For 16-ply graphite/epoxy specimens, the alarm voltage window, indicating no material damage, was 1.5 to 3.5 volts. In Fig. 9b the back-face reflection amplitude is slightly greater than 1.5 volts indicating undamaged material. When the specimen was inspected at the end of $5\frac{1}{2}$ lifetimes, the back-face reflection amplitude had decreased to a value of approximately 0.25 volts. The decrease to 0.25 volts took place in increments of approximately 0.25 volts per inspection. This implies that the severity of the material damage, which was determined to be a delamination in post-failure analysis, increased slowly as the fatigue cycles accumulated. The amplitude of the back-face reflection is of such a magnitude at the $5\frac{1}{2}$ lifetime inspection that the delamination had formed, but was still tight enough to allow passage of the ultrasound between the two adjoining plies.

By the $6\frac{1}{2}$ lifetime inspection, Fig. 10c, and up through the 9 lifetime inspection, Fig. 11a, only a faint back-face reflection amplitude can be seen. During this period it has been determined, using additional data not presented herein, that the delamination began to progress transversely across the

specimen from the hole towards the free-edge. This is evidenced by the tendrils of flawed area shown in the C-scan at the completion of 9 lifetimes of cycling, Fig. 11a. When the specimen was inspected after $9\frac{1}{2}$ lifetimes the delamination was severe enough that the ultrasound could not pass across the gap, hence, no back-face reflection was evident. The extent of the area of damage after 9 lifetimes (C-scan Fig. 11a) and the severity of the damage after $9\frac{1}{2}$ lifetimes (A-scan Fig. 11b) given adequate warning of the failure which occurred during the twentieth half-life of cycling. Similar trends are present in other areas of the specimen near the hole, but the volume of data required to show these trends would be extremely high. During the course of the investigation forty-one C-scans, 316 A-scan/RF spectrum photographs, and 120 feet of acoustic emission data was generated for this single specimen.

The photograph (Fig. 12) shows the failed specimen after removal from the fatigue chain. The massive delamination shown on the photo labeled "Failure Surface A-B" was the source of the data presented above. Presently, additional work is being done to correlate C-scan/A-scan/RF spectrum

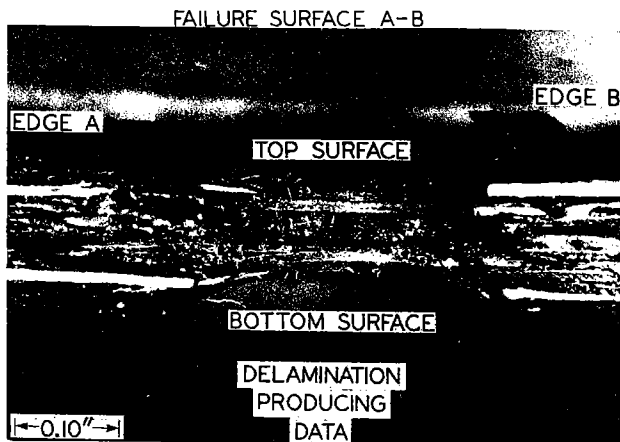


Fig. 12
Failed Specimen After Removal
From Fatigue Chain

data with the photographs of the failed specimen. The goal is to establish a relationship between A-scan/RF spectra signatures, and the type of material damage. In this manner, the criticality of the material damage of a component in-service could be assessed. This ultimately minimizes the need for replacement of good components because they appear to have strength reducing damage.

CONCLUSIONS

1. For the single specimen investigated, there was a clear correlation between acoustic emission activity and material damage.
2. Acoustic emission identified the exact point where major material damage occurred and, in doing so, predicted the failure that followed.
3. Critical flaw sizes must be determined for composites since the formation of noncritical flaws may have a high level of acoustic emission associated with it.
4. Additional work must be conducted to establish a correlation between specific acoustic emission outbursts to the type of material failure which caused the energy release, e.g., fiber breakage or matrix cracking.
5. More sensitive, less environmentally affected, acoustic emission transducers are necessary.
6. Both A-scan and RF spectrum data, when used in conjunction with ultrasonic C-scans, can give an indication of the extent, severity, and location of delaminations within a laminated composite material.

REFERENCES

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